The Philosophy of Physics

ROBERTO TORRETTI
University of Chile

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CHAPTER ONE

The Transformation of Natural Philosophy in the Seventeenth Century

Physics and philosophy are still known by the Greek names of the Greek intellectual pursuits from which they stem. However, in the seventeenth century they went through deep changes that have conditioned their further development and interaction right to the present day. In this chapter I shall sketch a few of the ideas and methods that were introduced at that time by Galileo, Descartes, and some of their followers, emphasizing those aspects that I believe are most significant for current discussions in the philosophy of physics.

Three reminders are in order before taking up this task.

First, in the Greek tradition, physics was counted as a *part* of philosophy (together with logic and ethics, in one familiar division of it) or even as *the whole* of philosophy (in the actual practice of "the first to philosophize" in Western Asia Minor and Sicily). Philosophy was the grand Greek quest for understanding everything, while physics or "the understanding of nature (*physis*)" was, as Aristotle put it, "about bodies and magnitudes and their affections and changes, and also about the sources of such entities" (*De Caelo*, $268^{a}1$–4). For all their boasts of novelty, the seventeenth-century founders of modern physics did not dream of breaking this connection. While firmly believing that nature, in the stated sense, is not all that there is, their interest in it was motivated, just like Aristotle's, by the philosophical desire to understand. And so Descartes compared philosophy with a tree whose *trunk* is physics; Galileo requested that the title of Philosopher be added to that of Mathematician in his appointment to the Medici court; and Newton's masterpiece was entitled *Mathematical Principles of Natural Philosophy*. The subsequent divorce of physics and philosophy, with a distinct cognitive role for each, although arguably a direct consequence of the transformation they went through together in the seventeenth century, was not consummated until later, achieving its classical formulation and justification in the work of Kant.

Second, some of the new ideas of modern physics are best explained by taking Aristotelian physics as a foil. This does not imply that the Aristotelian system of the world was generally accepted by European philosophers when Galileo and Descartes entered the lists. Far from it. The Aristotelian style of reasoning was often ridiculed as sheer verbiage. And the flourishing movement of Italian natural philosophy was decidedly un-Aristotelian. But the physics and metaphysics of Aristotle, which had been the *dernier cri* in the Latin Quarter of Paris *c.* 1260, although soon eclipsed by the natively Christian philosophies of Scotus and Ockam, achieved in the sixteenth century a surprising comeback. Dominant in European universities from Wittenberg to Salamanca, it was ominously wedded to Roman Catholic theology in the Council of Trent, and it was taught to Galileo at the university in Pisa and to Descartes at the Jesuit college in La Flèche; so it was very much in their minds when they thought out the elements of the new physics.

Finally, much has been written about the medieval background of Galileo and Descartes, either to prove that the novelty of their ideas has been grossly exaggerated – by themselves, among others – or to reassert their originality with regard to several critical issues, on which the medieval views are invariably found wanting. The latter line of inquiry is especially interesting, insofar as it throws light on what was really decisive for the transformation of physics and philosophy (which, after all, was not carried through in the Middle Ages). But here I must refrain from following it.[1]

1.1 Mathematics and Experiment

The most distinctive feature of modern physics is its use of mathematics and experiment, indeed its *joint* use of them.

A physical experiment artificially produces a natural process under carefully controlled conditions and displays it so that its development

[1] The medieval antecedents of Galileo fall into three groups: (i) the statics of Jordanus Nemorarius (thirteenth century); (ii) the theory of uniformly accelerated motion developed at Merton College, Oxford (fourteenth century); and (iii) the impetus theory of projectiles and free fall. All three are admirably explained and documented in Claggett (1959a). Descartes's medieval background is the subject of two famous monographs by Koyré (1923) and Gilson (1930).

can be monitored and its outcome recorded. Typically, the experiment can be repeated under essentially the same conditions, or these can be deliberately and selectively modified, to ascertain regularities and correlations. Experimentation naturally comes up in some rough and ready way in every practical art, be it cooking, gardening, or metallurgy, none of which could have developed without it. We also have some evidence of Greek experimentation with purely cognitive aims. However, one of our earliest testimonies, which refers to experiments in acoustics, contains a jibe at those who "torture" things to extract information from them.[2] And the very idea of *artificially* contriving a *natural* process is a contradiction in terms for an Aristotelian. This may help to explain why Aristotle's emphasis on *experience* as the sole source of knowledge did not lead to a flourishing of *experiment*, although some systematic experimentation was undertaken every now and then in late Antiquity and the Middle Ages (though usually not in Aristotelian circles).

Galileo, on the other hand, repeatedly proposes in his polemical writings experiments that, he claims, will decide some point under discussion. Some of them he merely imagined, for if he had performed them, he would have withdrawn his predictions; but there is evidence that he did actually carry out a few very interesting ones, while there are others so obvious that the matter in question gets settled by merely describing them. Here is an experiment that Galileo says he made. Aristotelians maintained that a ship will float better in the deep, open sea than inside a shallow harbor, the much larger amount of water beneath the ship at sea contributing to buoy it up. Galileo, who spurned the Aristotelian concept of lightness as a positive quality, opposed to heaviness, rejected this claim, but he saw that it was not easy to refute it by direct observation, due to the variable, often agitated condition of the high seas. So he proposed the following: Place a floating vessel in a shallow water tank and load it with so many lead pellets that it will sink if one more pellet is added. Then transfer the loaded vessel to another tank, "a hundred times bigger", and check how many more pellets must be added for the vessel to sink.[3] If, as one readily guesses, the difference is 0, the Aristotelians are refuted on this point.

[2] Plato (*Republic*, 537d). The verb βασανίζειν used by Plato means 'to test, put to the question', but was normally used of judicial questioning under torture. The acoustic experiments that Plato had in mind consisted in tweaking strings subjected to varying tensions like a prisoner on a rack.

[3] Benedetto Castelli (*Risposta alle opposizioni*, in Galileo, EN IV, 756).

Turning now to mathematics, I must emphasize that both its scope and our understanding of its nature have changed enormously since Galileo's time. The medieval *quadrivium* grouped together arithmetic, geometry, astronomy, and music, but medieval philosophers defined mathematics as the science of quantity, discrete (arithmetic) and continuous (geometry), presumably because they regarded astronomy and music as mere applications. Even so, the definition was too narrow, for some of the most basic truths of geometry – for example, that a plane that cuts one side of a triangle and contains none of its vertices inevitably cuts one and only one of the other two sides – have precious little to do with quantity. In the centuries since Galileo mathematics has grown broader and deeper, and today no informed person can accept the medieval definition. Indeed, the wealth and variety of mathematical studies have reached a point in which it is not easy to say in what sense they are one. However, for the sake of understanding the use of mathematics in modern physics, it would seem that we need only pay attention to two general traits. (1) Mathematical studies proceed from precisely defined assumptions and figure out their implications, reaching conclusions applicable to whatever happens to meet the assumptions. The business of mathematics has thus to do with the construction and subsequent analysis of concepts, not with the search for real instances of those concepts. (2) A mathematical theory constructs and analyzes a concept that is applicable to any collection of objects, no matter what their intrinsic nature, which are related among themselves in ways that, suitably described, agree with the assumptions of the theory. Mathematical studies do not pay attention to the objects themselves but only to the system of relations embodied in them. In other words, mathematics is about s*tructure*, and about *types* of structure.[4]

With hindsight we can trace the origin of structuralist mathematics to Descartes's invention of analytic geometry. Descartes was able to solve geometrical problems by translating them into algebraic equations because the system of relations of order, incidence, and congruence between points, lines, and surfaces in space studied by classical geometry can be seen to be embodied – under a suitable interpretation – in the set of ordered triples of real numbers and some of its subsets. The same structure – mathematicians say today – is *instantiated* by geo-

[4] For two recent, mildly different, philosophical elaborations of this idea see Shapiro (1997) and Resnik (1997).

metrical points and by real number triples. The points can be put – in many ways – into one-to-one correspondence with the number triples. Such a correspondence is known as a *coordinate system*, the three numbers assigned to a given point being its *coordinates* within the system. For example, we set up a *Cartesian coordinate system* by arbitrarily choosing three mutually perpendicular planes K, L, M; a given point O is assigned the coordinates $\langle a,b,c \rangle$ if the distances from O to K, L, and M are, respectively, $|a|$, $|b|$, and $|c|$, the choice of positive or negative a (respectively, b, c) being determined conventionally by the side of K (respectively, L, M) on which O lies. The *origin* of the coordinate system is the intersection of K, L, and M, that is, the point with coordinates $\langle 0,0,0 \rangle$. The intersection of L and M is known as the x-axis, because only the first coordinate – usually designated by x – varies along it, while the other two are identically 0 (likewise, the y-axis is the intersection of K and M, and the z-axis is the intersection of K and L). The sphere with center at O and radius r is represented by the set of triples $\langle x,y,z \rangle$ such that $(x - a)^2 + (y - b)^2 + (z - c)^2 = r^2$; thus, this equation adequately expresses the condition that an otherwise arbitrary point – denoted by $\langle x,y,z \rangle$ – lies on the sphere (O,r).

By paying attention to structural patterns rather than to particularities of contents, mathematical physics has been able to find affinities and even identities where common sense could only see disparity, the most remarkable instance of this being perhaps Maxwell's discovery that light is a purely electromagnetic phenomenon (§4.2). A humbler but more pervasive and no less important expression of structuralist thinking is provided by the time charts that nowadays turn up everywhere, in political speeches and business presentations, in scientific books and the daily press. In them some quantity of interest is plotted, say, vertically, while the horizontal axis of the chart is taken to represent a period of time. This representation assumes that time is, at least in some ways, structurally similar to a straight line: The instants of time are made to correspond to the points of the line so that the relations of betweenness and succession among the former are reflected by the relations of betweenness and being-to-the-right-of among the latter, and so that the length of time intervals is measured in some conventional way by the length of line segments.

Such a correspondence between time and a line in space is most naturally set up in the very act of moving steadily along that line, each point of the latter corresponding uniquely to the instant in which the mobile reaches it. This idea is present already in Aristotle's rebuttal of Zeno's "Dichotomy" argument against motion. Zeno of Elea claimed that an athlete could not run across a given distance, because before traversing any part of it, no matter how small, he would have to traverse one half of that part. Aristotle's reply was – roughly paraphrased – that if one has the time *t* to go through the full distance *d* one also has the time to go first through 1/2 *d*, namely, the first half of *t* (*Phys.* 233ª21 ss.). In fact, Zeno himself had implicitly mapped time into space – that is, he had assigned a unique point of the latter to each instant of the former – in the "Arrow", in which he argues that a flying arrow never moves, for at each instant it lies at a definite place. Zeno's mapping is repeated every minute, hour, and half-day on the dials of our watches by the motion of the hands, and it is so deeply ingrained in our ordinary idea of time that we tend to forget that time, as we actually live it, displays at least one structural feature that is not reflected in the spatial representation, namely, the division between past and future. (Indeed, some philosophers have brazenly proclaimed that this division is "subjective" – by which they mean illusory – so one would do well to forget it . . . if one can.)

There is likewise a structural affinity between all the diverse kinds of continuous quantities that we plot on paper. Descartes was well aware of it. He wrote that "nothing is said of magnitudes in general which cannot also be referred specifically to any one of them," so that there "will be no little profit in transferring that which we understand to hold of magnitudes in general to the species of magnitude which is depicted most easily and distinctly in our imagination, namely, the real extension of body, abstracted from everything else except its shape" (AT X, 441). Once all sorts of quantities are represented in space, it is only natural to combine them in algebraic operations such as those that Descartes defined for line segments.[5] Mathematical physics has been doing it for almost four centuries, but it is important to realize that at one time the idea was revolutionary. The Greeks had a well-developed calculus of proportions, but they would not countenance ratios between heterogeneous quantities, say, between distance and time, or between mass and volume. And yet a universal calculus of ratios would seem to be a fairly easy matter when ratios between homogeneous

[5] Everyone knows how to add two segments a and b to form a third segment $a + b$. Descartes showed how to find a segment $a \times b$ that is the *product* of a and b: $a \times b$ must be a segment that stands in the same proportion to a as b stands to the unit segment.

quantities have been formed. For after all, even if you only feel free to compare quantities of the same kind, the *ratios* established by such comparisons can be ordered by size, added and multiplied, and compared with one another as constituting a new species of quantity on their own. Thus, if length b is twice length a and weight w is twice weight v, then the ratio b/a is identical with the ratio w/v and twice the ratio $w/(v + v)$. Euclid explicitly equated, for example, the ratio of two areas to a ratio of volumes and also to a ratio of lengths (Bk. XI, Props. 32, 34), and Archimedes equated a ratio of lengths with a ratio of times (*On Spirals*, Prop. I). Galileo extended this treatment to speeds and accelerations. In the *Discorsi* of 1638 he characterizes uniform motion by means of four "axioms". Let the index i range over $\{1,2\}$. We denote by s_i the space traversed by a moving body in time t_i and by v_i the speed with which the body traverses space s_i in a fixed time. The body moves with *uniform motion* if and only if (i) $s_1 > s_2$ if $t_1 > t_2$, (ii) $t_1 > t_2$ if $s_1 > s_2$, (iii) $s_1 > s_2$ if $v_1 > v_2$, and (iv) $v_1 > v_2$ if $s_1 > s_2$. From these axioms Galileo derives with utmost care a series of relations between spaces, times, and speeds, culminating in the statement that "if two moving bodies are carried in uniform motion, the ratio of their speed will be the product of the ratio of the spaces run through and the inverse ratio of the times", which, if we designate the quantities concerning each body respectively by primed and unprimed letters, we would express as follows:

$$\frac{v}{v'} = \left(\frac{s}{s'}\right)\left(\frac{t'}{t}\right) \tag{1.1}$$

By taking the reciprocal value of the ratio of times, the ratio of speeds can also be expressed as a ratio of ratios:

$$\frac{v}{v'} = \left(\frac{s}{s'}\right)\Big/\left(\frac{t}{t'}\right) \tag{1.2}$$

If we now assume that the body to which the primed quantities refer moves with unit speed, traversing unit distance in unit time, eqn. (1.1.) can be rewritten as:

$$\frac{v}{1} = \left(\frac{s}{1}\right)\Big/\left(\frac{t}{1}\right) \tag{1.3}$$

which, except for the pedantry of writing down the 1's, agrees with the familiar schoolbook definition of constant or average speed.

1.2 Aristotelian Principles

The most striking difference between the modern view of nature and Aristotle's lies in the separation he established between the heavens and the region beneath the moon. While everything in the latter ultimately consists of four "simple bodies" – fire, air, water, earth – that change into one another and into the wonderful variety of continually changing organisms, the heavens consist entirely of aether, a simple body that is very different from the other four, which is capable of only one sort of change, viz., circular motion at constant speed around the center of the world. This mode of change is, of course, minimal, but it is incessant. The circular motion of the heavens acts decisively on the sublunar region through the succession of night and day, the monthly lunar cycle, and the seasons, but the aether remains immune to reactions from below, for no body can act on it.

This partition of nature, which was cheerfully embraced by medieval intellectuals like Aquinas and Dante, ran against the grain of Greek natural philosophy. The idea of nature as a unitary realm of becoming, in which everything acted and reacted on everything else under universal constraints and regularities, arose in the sixth century b.c. among the earliest Greek philosophers. Their tradition was continued still in the Roman empire by Stoics and Epicureans. Measured against it, Aristotle's system of the world appears reactionary, a sop to popular piety, which was deadly opposed to viewing, say, the sun as a fiery rock. But Aristotle's two-tiered universe was nevertheless unified by deep principles, which were cleverer and more stimulating than anything put forward by his rivals (as far as we can judge by the surviving texts), and they surely deserve no less credit than the affinity between Greek and Christian folk religion for Aristotle's success in Christendom. Galileo, Descartes, and other founding fathers of modern physics were schooled in the Aristotelian principles, but they rejected them with surprising unanimity. It will be useful to cursorily review those principles to better grasp what replaced them.

Aristotle observes repeatedly that the verb 'to be' has several meanings ("*being* is said in various ways" – *Metaph*. 1003^b5, 1028^a10). The ambiguity is manifold. We have, first of all, the distinction "according to the figures of predication" between *being a substance* – a tree, a horse, a person – and *being an attribute* – a quality, quantity, relation, posture, disposition, location, time, action, or passion – of substances.[6]

[6] 'Substance' translates οὐσία, a noun formed directly from the participle of the verb εἶναι, 'to be'. So a more accurate translation would be 'being, properly so called'.

Aristotle mentions three other such spectra of meaning, but we need only consider one of them, viz., the distinction between *being actually* and *being potentially*. This is the key to Aristotle's understanding of organic development, which is his paradigm of change (just as organisms are his paradigm of substance – *Metaph.* 1032^{a}19). Take a corn seed. Actually it is only a small hard yellow grain. Potentially, however, it is a corn plant. While it lies in storage the potentiality is dormant; yet its presence can be judged from the fact that it can be destroyed, for example, if the seed rots, or is cooked, or if an insect gnaws at it. The potentiality is activated when the seed is sown and germinates. From then on the seed is taken over by a process in the course of which the food it contains, plus water and nutrients sucked up from the environment, are organized as the leaves, flowers, and ears of a corn plant. The process is guided by a goal, which our seed inherited from its parents. This is none other than the *morphe* ('form') or *eidos* ('species') of which this plant is an individual realization. The form is that by virtue of which *this* is a corn plant and *that* a crocodile. If a substance is fully and invariably what it is, its form is all that there is to it. Such are the gods. But a substance that is capable of changing in any respect is a compound of form and *matter* (*hyle*, literally 'wood'), a term under which Aristotle gathers everything that is actively or dormantly potential in a substance. Only such substances can be said to have a 'nature' (*physis*) according to Aristotle's definition of this term, that is, an inherent principle of movement and rest.

Although the development of organisms obviously inspired Aristotle's overall conception of change, it is not acknowledged as a distinct type in his classification of changes. This is tailored to his figures of predication. He distinguishes (*a*) the generation and destruction of substances, and (*b*) three types of change in the attributes of a given substance, which he groups under the name *kinesis* – literally, 'movement' –, viz., (b_1) alteration or change in quality, (b_2) growth and wane or change in quantity, and (b_3) motion proper – *phora* in Greek – or change of location. We need consider only (*a*) and (b_3), the former because it was believed to involve a sort of matter – in the Aristotelian sense – that eventually came to be conceived as matter in the un-Aristotelian modern sense and the latter because change of location was the only kind of change that this new-fangled matter could really undergo.

But the modern thinkers we are presently interested in were taught to say 'substance' (Lat. *substantia*) for Aristotle's οὐσία, so we better put up with it.

Motion (*phora*) was viewed by Aristotle as one of several kinds of movement (*kinesis*). Organic growth was another, somehow more revealing, kind. He wrote that *kinesis* is "the actuality of potential being as such" (*Phys*. $201^{a}11$), a definition that Descartes dismissed as balderdash (AT X, 426; XI, 39) but that surely makes sense with regard to a corn seed that grows into a plant when its inborn potentialities are actualized. Movement is thus conceived by Aristotle as a way of being. Zeno's arrow surely *is* at one place at any one time, but it *is moving*, not *resting* there, for it is presently exercising its natural potentiality for resting elsewhere, namely, at the center of the universe, where, according to Aristotle, it would naturally come to stand if allowed to fall without impediment.

I mentioned previously Aristotle's doctrine of the four simple bodies from which everything under the moon is compounded. They are characterized by their simple qualities, one from each pair of opposites, hot/cold and wet/dry, and their simple motions, which motivate their classification as light or heavy. Thus fire is *hot*, *dry*, and also *light*, in that it moves naturally in a straight line *away* from the center of the universe until it comes to rest at the boundary of the nethermost celestial sphere; earth is *dry*, *cold*, and also *heavy*, that is, it moves naturally in a straight line *toward* the center of the universe until it comes to rest at it; water is *wet*, *cold*, and *heavy* (though less so than earth); and air is *hot*, *wet*, and *light* (though less so than fire). Aristotle's notion of heaviness and lightness can grossly account for the familiar experience of rising smoke, falling stones, and floating porous timber.[7] But what about the full variety of actual motions? To cope with it, Aristotle employs some additional notions. Although the natural upward or downward straight-line motion of the simple elements is inherent in their compounds, the heaviness of plants and animals – which presumably consist of all four elements, but mostly of earth and water – can be overcome by their supervenient forms. Thus ivy climbs

[7] A reflective mind will find fault with them even at the elementary level. Imagine that a straight tunnel has been dug across the earth from here to the antipodes. Aristotelian physics requires that a stone dropped down this tunnel should stop dead when it reaches the center of the universe (i.e., of the earth), even though at that moment it would be moving faster than ever before. Albert of Saxony, who discussed this thought experiment *c.* 1350, judged the Aristotelian conclusion rather improbable. He expected the stone to go on moving toward the antipodes until it was stopped by the downward pull toward the center of the earth (which, after the stone has passed through it, is exerted, of course, in the opposite direction).

walls and goats climb rocks. The simple bodies and their compounds are also liable to *forced* motion (or rest) *against* their natures, through being pushed/pulled (or stopped/held) by other bodies that move (or rest) naturally. Thus a heavy wagon is forced to move forward by a pair of oxen and a heavy ceiling is stopped from falling by a row of standing pillars. But Aristotelian physics has a hard time with the motion of missiles. This must be forced, for missiles are heavy objects that usually go higher in the first stage of their motion. Yet they are separated from the mover that originally forces them to move against their nature. Aristotle (*Phys.* 266^{b}27–267^{a}20) contemplates two ways of dealing with this difficulty. The first way is known as *antiperistasis*: The thrown missile displaces the air in front of it, and the nimble air promptly moves behind the missile and propels it forward and upward; this process is repeated continuously for some time after the missile has separated from the thrower. This harebrained idea is mentioned approvingly in Plato's *Timaeus* (80a1), but Aristotle wisely keeps his distance from it. Nor does he show much enthusiasm for the second solution, which indeed is not substantially better. It assumes that the thrower confers a forward and upward thrust to the neighboring air, which the latter, being naturally light, retains and communicates to further portions of air. This air pushes the missile on and on after it is hurled by the thrower.[8]

Despite its obvious shortcomings, Aristotle's theory of the natural motions of light and heavy bodies is the source of his sole argument for radically separating sublunar from celestial physics. It runs as follows. Simple motions are the natural motions of simple bodies. There are two kinds of simple motions, viz., straight and circular. But all the simple bodies that we know from the sublunar region move naturally in a straight line. Therefore, there must be a simple body whose natural motion is circular. Moreover, just as the four familiar simple bodies move in straight lines to and from the center of the universe, the fifth simple body must move in circles around that center. The nightly spectacle of the rotating firmament lends color to this surpris-

[8] John Philoponus, commenting on Aristotle's *Physics* in the sixth century a.d., remarked that if this theory of missile motion were right, one should be able to throw stones most efficiently by setting a large quantity of air in motion behind them. This is exactly what Renaissance Europe achieved with gunpowder. However, the unexpectedly rich and precise experience with missiles provided by modern gunnery has not vindicated Aristotle.

ing argument. Its conclusion agrees well, of course, with fourth-century Greek mathematical astronomy, which analyzed the wanderings of the sun, moon, and planets as resulting from the motion of many nested spheres linked to one another and rotating about the center of the universe with different (constant) angular velocities.[9]

Changes of quality, size, or location, grouped by Aristotle under the name of *kinesis*, suppose a permanent substance with varying attributes. But Aristotelian substances also change into one another in a process by which one substance is generated as another is being destroyed. The generation of plants and animals can be understood as the incorporation of a new form in a suitable combination of simple bodies behaving pliably as matter. But the transmutation of one simple body into another – which, according to Aristotle, occurs incessantly in the sublunar realm – cannot be thus understood. However, the traditional reading of Aristotle assumes that in such cases the change of form is borne by formless matter, an utterly indeterminate being that potentially is anything and yet, despite its complete lack of definition, ensures the numerical identity of what was there and is destroyed with what thereupon comes into being. Recent scholars have questioned this interpretation and the usual understanding of the Aristotelian expression 'prime matter' (*prote hyle*) as referring to the alleged ultimate substratum of radical transformations.[10] Their view makes Aristotle into a better philosopher than he would otherwise be, but this is quite irrelevant to our present study, for the founders of modern science read Aristotle in the traditional way. Indeed, what they call 'matter' appears to have evolved from the 'prime matter' of Aristotelian tradition in the course of late medieval discussions. Ockam, for example, held that prime matter, if it is at all real – as he thought it must be to account for the facts of generation and corruption –, must in some way be actual: "I say that matter is a certain kind of act, for matter exists in the realm of nature, and in this sense, it is not potentially every act for

[9] It is important to realize that the celestial physics of Aristotle was deeply at variance with the more accurate system of astronomy that was later developed by Hipparchus and Apollonius and which medieval and Renaissance Europe received through Ptolemy. Each Ptolemaic planet (including the Sun and the Moon) moves in a circle – the *epicycle* – whose center moves in another circle – the *deferent* – whose center is at rest. But not even the deferent's center coincides with the Aristotelian "center of the universe", that is, the point to or from which heavy and light bodies move naturally in straight lines.

[10] King (1956), Charlton (1970, appendix). For a defense of the traditional reading see Solmsen (1958), Robinson (1974), and C. J. F. Williams (1982, appendix).

it is not potentially itself."[11] Such matter "is the same in kind in all things which can be generated and corrupted".[12] Moreover, although the heavenly bodies are incorruptible, Ockam was convinced that they too were formed from that same kind of matter:

> It seems to me then that the matter of the heavens is the same in kind as that of things here below, because as has been frequently said: *one must never assume more than is necessary*. Now there is no reason in this case that warrants the postulation of a different kind of matter here and there, because every thing explained by assuming different matters can be equally accounted for, or better explained by postulating a single kind.[13]

1.3 Modern Matter

'Matter' is just the anglicized form of *materia*, a Latin word meaning 'timber' that Cicero deftly chose for translating Aristotle's *hyle*. 'Matter' may thus in all fairness be seen as a contribution of philosophy to ordinary English. Yet its everyday meaning is a far cry from Aristotle's. In fact, the term could hardly keep its Aristotelian sense in a Christian setting. Christian theologians cherished Plato's myth of the divine artisan who molds matter[14] as potter's clay, but their God did not *encounter* matter as a coeval 'wet-nurse of becoming' (*Timaeus* 52d) but *created* it out of nothing. As an *actual* creature of God's will, Christian matter cannot be purely potential and indeterminate, but comes with all the properties required for God's purpose. Indeed, some seventeenth-century authors thought it most fitting that the world created by an all-knowing, all-powerful God should consist of a single universal stuff that develops automatically into its present splendor from a wisely chosen initial configuration, with no further intervention on His part. Be that as it may, surely the Deity of Christian philosophy knew exactly what He wanted when He created the world and could bring forth a material thoroughly suited to His ends.

Both Plato and Aristotle held that an exact science of nature was

[11] Ockam (*Summulae in libros Physicorum*, Pars I, cap. 16, fol. 6*ra*) quoted in Wolter (1963, p. 134).

[12] Ockam (*Expositio super octo libros Physicorum*, Lib. I, com. 1) quoted in Wolter (1963, p. 130).

[13] Ockam (*Reportatio in Sentent. II*, q. 22, D) quoted in Wolter (1963, p. 146) (my italics).

[14] Plato's word is χώρα, which in ordinary Greek meant 'extension, room, place', and often 'land, country'.

precluded by matter's inherent potentiality for being otherwise. Just as a geometer admires an excellent drawing but does not expect to establish true geometrical relations by studying it, so a "real astronomer" will judge "that the sky and everything in it have been put together by their maker in the most beautiful way in which such works can be put together, but will – don't you think? – hold it absurd to believe that the metrical relation (*symmetrian*) of night to day, of these to month, and month to year, and of the other stars to these and to each other are ever the same and do not deviate at all anywhere, although they are corporeal and visible" (Plato, *Rep.* 530a–b). The predictive success of Eudoxus's planetary models caused Plato to recant, and his spokesman in *Laws* (821b) asserts that "practically all Greeks now slander those great gods, Sun and Moon", for "we say that they and some other stars besides them never go along the same path, and we dub them roamers (*planeta*)." For Aristotle, heavenly motions are exact because they are steered directly by gods, but even gods could not achieve this if the heavens did not consist of aether, which admits no change except rotation on the spot. All other matter is incapable of such unbending regularity, and therefore sublunar events are not liable to mathematical treatment. Therefore, according to Aristotle, physics should not rely on geometrical notions such as 'concave', but rather use concepts like 'snub', which is confined to noses and involves a reference to facial flesh (*Phys.* 194^{a}13; cf. *De an.* 431^{b}13, *Metaph.* 1025^{b}31, 1064^{a}24, 1030^{b}29).

The idea of *created* matter does away with all such limitations. Indeed, the conception of universal matter professed with comparatively minor variations by Galileo, Descartes, and Newton seems expressly designed for mathematical treatment, or, more precisely, for treatment with the resources of seventeenth-century mathematics. The gist of it is concisely stated by Robert Boyle: "I agree with the generality of philosophers, so far as to allow that there is one catholic or universal matter common to all bodies, by which I mean a substance extended, divisible, and impenetrable" (1666, in SPP, p. 18). Matter being one, something else is required to account for the diversity we see in bodies. However, this additional principle need not consist of immaterial Aristotelian forms, but simply of the diverse motions that different parts of matter have with respect to each other. As Boyle puts it: "To discriminate the catholic matter into variety of natural bodies, it must have motion in some or all its designable parts; and that motion must have various tendencies, that which is in this part of the matter tending one way, and that which is in that part tending another" (Ibid.). Indeed, the actual division of matter into parts of different sizes and shapes is "the genuine effect of variously determined motion"; and "since experience shows us (especially that which is afforded us by chemical operations, in many of which matter is divided into parts too small to be singly sensible) that this division of matter is frequently made into insensible corpuscles or particles, we may conclude that the minutest fragments, as well as the biggest masses, of the universal matter are likewise endowed each with its peculiar bulk and shape" (SPP, p. 19). "And the indefinite divisibility of matter, the wonderful efficacy of motion, and the almost infinite variety of coalitions and structures that may be made of minute and insensible corpuscles, being duly weighed, I see not why a philosopher should think it impossible to make out, by their help, the mechanical possibility of any corporeal agent, how subtle or diffused or active soever it be, that can be solidly proved to be really existent in nature, by what name soever it be called or disguised" (Boyle 1674, in SPP, p. 145).

This view justifies Galileo's assertion that the universe is like a book open in front of our eyes in which anyone can read, provided that she or he understands the "mathematical language" in which it is written – for "its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word of it" (1623, §6; EN VI, 232). It also implies the notorious distinction between the inherent "primary" qualities of bodies, viz., number, shape, motion, and their mind-dependent "secondary" qualities, viz., all the more salient features they display to our senses.[15] As Galileo explains further on in the same book:

[15] The distinction can be traced back to Democritus's dictum "By custom, sweet; by custom, bitter. By custom, hot; by custom, cold. By custom, color. In truth: atoms and void" (DK 68.B.9). But there are deep conceptual differences between ancient atoms and modern matter. Greek atomism is a clever and imaginative reply to Eleatic ontology: *Being* cannot change, but if allowance is made for Non-Being in the guise of the void, there is room for plurality and motion, and this is enough to account for the variety of appearances. Each atom is indivisible (*a-tomos*) precisely because it is a specimen of Parmenides's changeless Being. Modern matter is not subject to such ontological constraints. Descartes explicitly rejects atoms and denies the possibility of a void. Even Boyle, who invested much ingenuity and effort in pumping air out of bottles, was not committed to the existence of a true vacuum absolutely devoid of matter of any sort. And, although Boyle believed that matter is stably divided into very little bodies, he did not think that these *corpuscles* were indivisible in principle.

> As soon as I conceive a matter or corporeal substance I feel compelled to think as well that it is bounded and shaped with this or that figure, that it is big or small in relation to others, that it is in this or that place, in this or that time, that it moves or rests, that it touches or does not touch another body, that it is one, or few, or many; and I cannot separate it from these conditions by any stretch of the imagination. But that it must be white or red, bitter or sweet, sonorous or silent, of pleasant or unpleasant smell, I do not feel my mind constrained to grasp it as necessarily attended by such conditions. Indeed, discourse and sheer imagination would perhaps never light on them, if not guided by the senses. Which is why I think that tastes, odors, colors, etc. are nothing but names with regard to the object in which they seem to reside, but have their sole residence in the sensitive body, so that if the animal is removed all such qualities are taken away and annihilated. But since we have bestowed on them special names, different from those of the other primary and real attributes, we wish to believe that they are also truly and really different.
>
> (Galileo 1623, §48; EN VI, 347–48)

Less notorious but no less remarkable is the similarity between Galileian matter and the Aristotelian aether: Both are imperishable and unalterable, and capable only of change by motion. (Indeed, Galileo held at times that the natural motion of all matter is circular, though not indeed about the center of the universe.) Looking at a museum exhibit of lunar rocks we admire Galileo's hunch that they would turn out to be just sublunar stuff. But the very familiarity of that sight may cause us to overlook the main drift of his work. His aim was not to conquer heaven for terrestrial physics (a dismal prospect, given the state of the latter *c.* 1600), but rather to apply right here on earth exact mathematical concepts and methods such as those employed successfully in astronomy. The modern concept of matter made this viable.

The modern concept of matter also conferred legitimacy on experimental inquiry in the manner I shall now explain. If natural change involves the supervenience and operation of "forms" that scientists do not know, let alone control, and there is moreover an essential distinction between natural and forced changes, it is highly questionable that one can learn anything about natural processes by experiment. But if all bodies consist of a single uniform and changeless stuff, and all variety and variation results exclusively from the motion and reconfiguration of its parts and particles, the distinction between natural and forced changes cannot amount to much. If all that ever happens in the physical world is that this or that piece of matter changes its position and velocity, a scientist's intervention can only produce divisions and displacements such as might also occur without him. Experiments can be extremely helpful for studying – and mastering – the ways of nature because they are just a means of achieving faster, more often, and under human control, changes of the only kind that matter allows, viz., by "local motion, which, by variously dividing, sequestering, transposing, and so connecting, the parts of matter, produces in them those accidents and qualities upon whose account the portion of matter they diversify comes to belong to this or that determinate species of natural bodies" (Boyle 1666, in SPP, p. 69).

The most resolute and forceful spokesman for the modern idea of matter was Descartes (1641, 1644). He asked himself what constitutes the reality of any given body, for example, a piece of wax fresh from the honeycomb – not its color, nor its smell, nor its hardness, nor even its shape, for all these are soon gone if the piece of wax is heated, and yet the piece remains. But, says Descartes, when everything that does not belong to it is removed and we see what is left, we find "nothing but something extended, flexible, mutable" (AT VII, 31). Indeed, "extension in length, breadth and depth", its division into parts, and the number, sizes, figures, positions, and motions of these parts (AT VII, 50) are all that we can clearly and distinctly conceive in bodies and therefore provide the entire conceptual stock of physics. Obviously, *motion* is the sole idea that Cartesian physics adds to Cartesian geometry. Moreover, it is defined by Descartes in geometric terms:

> Motion as ordinarily understood is nothing but *the action by which a body goes from one place to another*. [. . .] But if we consider what must be understood by motion in the light not of ordinary usage, but of the truth of the matter, we can say that *it is the transport of one part of matter or of one body, from the vicinity of those bodies which are immediately contiguous to it, and are regarded as being at rest, to the neighborhood of others*. By *one body* or *one part of matter* I understand all that is transported together, even if this, in turn, consists perhaps of many parts which have other motions. And I say that motion is *the transport,* not the force or action which transports, to indicate that motion is always in the mobile, not in the mover [. . .]; and that it is a property (*modus*) of it, and not a thing that subsists by itself; just as shape is a property of the thing shaped and rest of the thing at rest.
>
> (Descartes 1644, II, arts. 24, 25; AT VIII, 53–54)

Matter as extension being naturally inert, the property of motion is bestowed on several parts of it by God; indeed the actual division of matter into distinct bodies is a consequence of the diverse motions of its different parts. While Descartes is emphatic that motion is just change of relative position, he was well aware that in collisions it behaves like an acting force. To account for this, Descartes developed the concept of a *quantity of motion*, which resides in the moving body and is transferred from it to the bodies it collides with according to fixed rules. According to Descartes, the immutability of God requires that the quantity of motion He conferred on material things at creation should remain the same forever. Descartes computes the quantity of motion of a given body by multiplying its *speed* by its *quantity of matter*. This notion led to the classical mechanical concept of momentum (*mass* × *velocity*), so I shall call it *Cartesian momentum*. Two important differences must be emphasized: (i) If extension is the sole attribute of matter, the quantity of matter can only be measured by its volume, so there is no room in Cartesian physics for a separate concept of mass. (ii) Cartesian momentum is the product of the quantity of matter by (undirected) *speed*, not by (directed) *velocity*, so, in contrast with classical momentum, it is a scalar, not a vector. This raises questions to which I now turn.

(i) A ball of solid gold can cause much more damage on impact that a ball of cork of the same size moving with the same speed. How does Cartesian physics cope with this fact? If matter coincides with extension, there are no empty interstices in the cork. However, the quantity of motion borne by either ball depends on their respective quantity of matter, that is, the volume of all the matter that moves together, and within the outer limits of each ball there are interstices filled with matter that does not move with the rest. This Cartesian solution is quaint, for one normally expects a moving sponge to drag the air in its pores, but it is not altogether absurd.

(ii) The only principle of Cartesian physics that still survives is the principle of inertia: A moving body, if not impeded, will go on moving with the same speed in the same direction. Here we have a universal tendency that – one would think – underlies the conservation of motion in a system of two or more bodies that impede each other by collision. Now, if direction is one of the main determinants of the persistent motion contributed by each colliding body, why did Descartes exclude it from his definition of the quantity of motion conserved in the system? This is not an easy question, as we shall now see.

The principle of inertia is embodied in two "natural laws" that Descartes derives "from God's immutability":

> The *first* law is: Each thing, in so far as it is simple and undivided, remains by itself always in the same state, and never changes except through external causes. Thus if a piece of matter is square, we shall easily persuade ourselves that it will remain square for ever, unless something comes along from elsewhere which changes its shape. If it is at rest, we do not believe it will ever begin to move, unless impelled by some cause. Nor is there any more reason to think that if a body is moving it will ever interrupt its motion out of its own initiative and when nothing else impedes it.
>
> . . . .
>
> The second natural law is: each part of matter considered by itself does not tend to proceed moving along slanted lines, but only in straight lines. [. . .] The reason for this rule, like that for the preceding one, is the immutability and simplicity of the operation by which God conserves motion in matter. For He conserves it precisely as it is at the moment when He conserves it, without regard to what it was a little earlier. Although no motion can take place in an instant, it is nevertheless evident that every thing that moves, at every instant which can be indicated while it moves, is determined to continue its motion in a definite direction, following a straight line, not any curved line.
>
> (Descartes 1644, II, arts. 37, 39; AT VIII, 63–64)

With hindsight we scoff at Descartes for overlooking that an instant tendency to move in a particular direction may well be coupled with an instant tendency to change that direction in a given direction and still with a third tendency to change the direction of change, and so on, so that any spatial trajectory could result from a suitable combination of such directed quantities.[16] But this does not detract from the novelty and significance of his insight: Although motion cannot be carried out *in* an instant, it can exist *at* an instant, not as "the actuality of potential being" (whatever this might mean), but as a fully real directed quantity. Still, how could this insight be entirely forgotten in the definition of Cartesian momentum? It is true that vector algebra and analysis are creatures of the nineteenth century. But the addition

[16] For example, a particle moving at instant t with unit velocity $\mathrm{v}(t)$ in a particular direction can also be endowed at that instant with, say, unit acceleration $\mathrm{v}'(t)$. If $\mathrm{v}'(t)$ is perpendicular to $\mathrm{v}(t)$ and its rate of change $\mathrm{v}''(t) = 0$, the particle moves with uniform speed on a circle of unit radius. In Newtonian dynamics, acceleration is always due to external forces and the Principle of Inertia is preserved, but this is not the outcome of a logical necessity, let alone a theological one, as Descartes claims (see §2.1).

of directed quantities by the parallellogram rule dates at least from the sixteenth century, and Descartes used it in his *Dioptrique* and subsequently discussed it at length with Fermat in 1637 in correspondence mediated by Mersenne (AT I, 357–59, 451–52, 464–74).[17]

Why then did he not resort to it for adding the motions of colliding bodies? In §1.5 we shall consider some devastating criticism of Cartesian physics by Leibniz and Huygens, which ultimately results from this omission. Some scholars think that Descartes could not combine motions by the parallellogram rule because he shared the Aristotelian belief that "each individual body has only one motion which is peculiar to it".[18] I cannot go further into this matter here, but there is one interesting consequence of the definition of Cartesian momentum as a scalar that I must mention. According to Descartes the human mind is able to modify – he does not say how – the direction of motion of small particles in the pineal gland although it cannot alter their quantity of motion. This ensures that a person's behavior can depend on her free will. This escape provision for human freedom is not available if the unalterable quantity of motion is a vector instead of a scalar.

1.4 Galileo on Motion

Galileo was 32 years older than Descartes and was already philosophizing about motion when the latter was born in 1596. Galileo's early writings criticize some Aristotelian tenets and show the influence of the impetus theory. According to this view, which was fathered by John Philoponus in late Antiquity and revived and further elaborated in the fourteenth century, the violent motion of missiles continues after they separate from the mover because the initial thrust impresses

[17] By this rule, if v and w are two directed quantities represented by arrows with a common origin *p*, their sum v + w is a directed quantity represented by an arrow from *p* to the opposite vertex of the parallellogram formed by the arrows representing v and w. Compare Newton's rule for the composition of forces, illustrated in Fig. 7 (§2.2).

[18] Descartes (1644, II art. 31), as cited in Damerow et al. (1992, p. 105). Taken in context, the passage does not, in my view, seem to support their opinion. Descartes wrote: "Etsi autem *unumquodque corpus habeat tantum unum motum sibi proprium*, quoniam ab unis tantum corporibus sibi contiguis et quiescentibus recedere intelligitur, participare tamen etiam potest ex aliis innumeris, si nempe sit pars aliorum corporum alios motus habentium" (AT VII, 57; I have italicized the sentence quoted by Damerow et al.).